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COHERENCE THEORY WITH SPECIAL REFERENCE TO ENERGY TRANSFER. (U)
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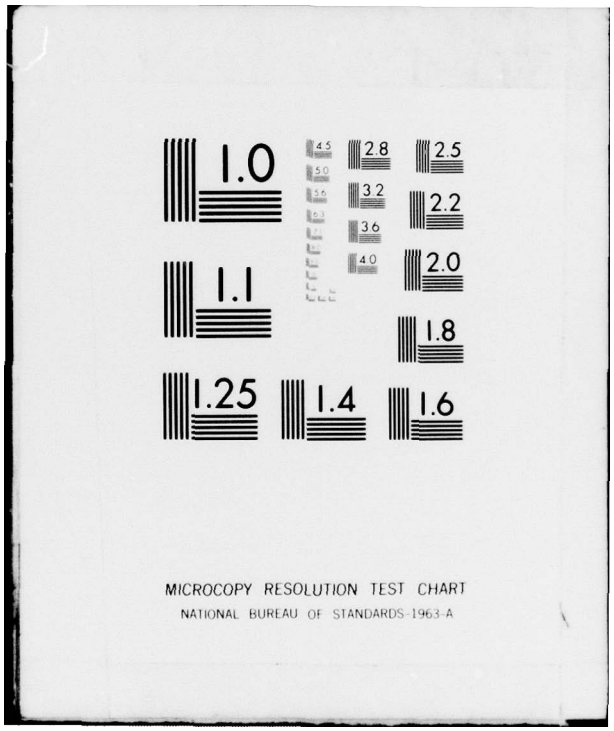
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A summary is presented of research carried out under Grant No. DAAG29 77 G 0006, covering the period October 10, 1976 - October 9, 1979. Most of the research was concerned with improvements of the usual phenomenological theory of radiative energy transfer and with the elucidation of the connection between that theory and the new rigorous stochastic theory of fluctuating wave fields.

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COHERENCE THEORY WITH SPECIAL REFERENCE TO ENERGY TRANSFER

LEVEL II

FINAL REPORT

GRANT NO. DAAG29-77-G-0006

PREPARED BY

EMIL WOLF

NOVEMBER 1979

SPONSORED BY THE U. S. ARMY RESEARCH OFFICE

THE UNIVERSITY OF ROCHESTER

DEPARTMENT OF PHYSICS AND ASTRONOMY

ROCHESTER, NEW YORK

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COHERENCE THEORY WITH SPECIAL REFERENCE TO ENERGY TRANSFER

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The University of Rochester
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Rochester, New York 14627

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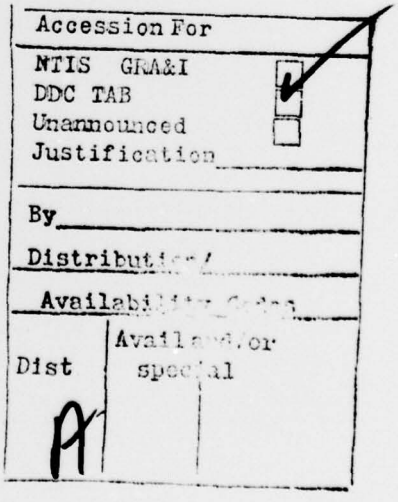

I. INTRODUCTION

In this report, a summary is presented of research carried out under Grant No. DAAG29-77-G-0006, covering the period October 10, 1976 - October 9, 1979. Most of the research was concerned with improvements of the usual phenomenological theory of radiative energy transfer and with the elucidation of the connection between that theory and the new rigorous stochastic theory of fluctuating wave fields.

In the early stages of this research, it was shown that a theory put forward by V. I. Tatarskii in 1971 contains an assumption that restricts its validity to fields that are statistically homogeneous. A theory was then formulated, free of this restriction, for radiation from a planar source of any state of coherence. It is based on second-order scalar coherence theory of the optical field. It was found that one cannot associate a radiance function with a finite source of any state of coherence that would satisfy all the usual postulates of conventional radiometry. However, it was shown that a radiance function may be defined as an appropriate linear transform of the second-order coherence function that leads to correct expectation values of quantities that are normally measured in experiments. The theory was applied to analyze radiation generated by various model sources. In particular, it was found that certain types of sources that may be spatially almost incoherent in the global sense, may produce the same far-zone distribution of optical intensity as a completely coherent laser source.

In addition to these investigations concerned with radiation from fluctuating sources in free space, a generalization of some of the results was also obtained for radiative energy transfer in a certain class of randomly fluctuating media (the so-called quasi-homogeneous media). Relations were obtained that connect the extinction coefficient and

the scattering coefficient (that are introduced heuristically in the conventional theory of radiative energy transfer) to the stochastic characteristics of the medium.

Some extensions of an earlier theory put forward by the Principal Investigator for the present grant [E. Wolf, Phys. Rev. D13 (1976), 869] for radiative energy transfer in stochastic electromagnetic fields in free space were also obtained. Unlike in much of the previously published work, the polarization properties of the field are here taken into account. Exact differential equations were obtained for the so-called angular components of the expectation values of the electromagnetic energy density of the momentum density that may be considered to be rigorous transport equations for these quantities in free space.

Several investigations that have a close bearing on the main topic of these researches were also carried out. Among these was a study of the similarities and the differences between the stochastic equations for classical and quantum distribution function and an investigation as to the precise nature of the far field of a gaussian beam.

Full accounts of our researches are contained in 19 publications. Titles, authors and journal references are listed on pages 3 and 4. Summaries of these publications are given on pages 5 - 13. Some of the results, obtained by a graduate research assistant while employed on this project, formed part of a Ph.D. thesis at the University of Rochester. Particulars are given on page 14. A list of scientific personnel that took part in this project is given on page 15.

II. LIST OF PUBLICATIONS

1. E. COLLETT, J. T. FOLEY and E. WOLF: "On an Investigation of Tatarskii into the Relationship between Coherence Theory and the Theory of Radiative Transfer" [J. Opt. Soc. Amer. 67, 465 (1977)].

2. M. S. ZUBAIRY and E. WOLF: "Exact Equations for Radiative Transfer of Energy and Momentum in Free Electromagnetic Fields" [Opt. Commun. 20, 321 (1977)].

3. M. D. SRINIVAS and E. WOLF: "Stochastic Equations for Classical and Quantum Distribution Functions" [Statistical Mechanics and Statistical Methods in Theory and Application, ed. U. Landman, Plenum Publishing Corp., New York (1977) p. 219].

4. E. COLLETT and E. WOLF: "Is Complete Spatial Coherence Necessary for the Generation of Highly Directional Light Beams?" [Opt. Letters 2, 27 (1978)].*

5. A. T. FRIBERG: "On the Question of the Existence of Nonradiating Primary Planar Sources of Finite Extent", [J. Opt. Soc. Amer. 68, 1281 (1978)].†

6. A. T. FRIBERG: "On the Existence of a Radiance Function for a Partially Coherent Planar Source" [Coherence and Quantum Optics IV, ed. L. Mandel and E. Wolf, Plenum Publishing Corp., New York (1978) p. 449].#

7. E. WOLF and M. S. ZUBAIRY: "Radiative Energy Transfer in Scalar Wave Fields" [Coherence and Quantum Optics IV, ed. L. Mandel and E. Wolf, Plenum Publishing Corp., New York (1978) p. 457].

8. M. S. ZUBAIRY: "Radiative Energy Transfer in the Presence of Random Source Distributions" [Coherence and Quantum Optics IV, ed. L. Mandel and E. Wolf, Plenum Publishing Corp., New York (1978) p. 459].

9. E. WOLF: "The Radiant Intensity from Planar Sources of Any State of Coherence" [J. Opt. Soc. Amer. 68, 1597 (1978)].

10. A. T. FRIBERG: "On the Existence of a Radiance Function for Finite Planar Sources of Arbitrary States of Coherence" [J. Opt. Soc. Amer. 69, 192 (1979)]. **#

11. J. T. FOLEY and E. WOLF: "Note on the Far Field of a Gaussian Beam" [J. Opt. Soc. Amer. 69, 761 (1979)].

12. E. WOLF and E. COLLETT: "Partially Coherent Sources which Produce the Same Far-Field Intensity Distribution as a Laser" [Opt. Commun. 25, 293 (1978)].*

13. R. ROY and M.S. ZUBAIRY: "Analytic Solutions of the Optical Bistability Equations for a Standing Wave Cavity" (Submitted to Opt. Commun.).††##

14. M. S. ZUBAIRY: "Radiative Energy Transfer in a Randomly Fluctuating Medium" (Submitted to J. Opt. Soc. Amer.).

15. R. ROY and M.S. ZUBAIRY: "Beyond the Mean Field Theory of Dispersive Optical Bistability" (Submitted to Phys. Rev. A).††##

II. PUBLICATIONS (cont'd)

16. S. SINGH and M. S. ZUBAIRY: "Quantum Theory of a Two-Mode Laser with Coupled Transitions" (Submitted to Phys. Rev. A).##

17. M. S. ZUBAIRY: "Effect of Cooperative Atomic Interactions on Photon Statistics in a Single-Mode Laser" (To be published in Phys. Rev. A).

18. E. COLLETT and E. WOLF: "Beams Generated by Gaussian Quasi-Homogeneous Sources" (Submitted to Opt. Commun.).*

19. A. T. FRIBERG: "Effects on Coherence in Radiometry", in "Applications of Optical Coherence", Proc. Soc. Photo. Opt. Instr. Engs., 194, (1979) (In Press).+

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†† Work supported in part by the National Science Foundation

Work supported in part by the Air Force Office of Scientific Research

III. SUMMARIES OF PUBLICATIONS:

1. E. COLLETT, J. T. FOLEY and E. WOLF

ON AN INVESTIGATION OF TATARSKII INTO THE RELATIONSHIP BETWEEN COHERENCE THEORY AND THE THEORY OF RADIATIVE TRANSFER

J. OPT. SOC. AMER. 67, 465 (1977)

In an investigation into the foundations of the theory of radiative energy transfer, Tatarskii (1971) postulated a certain relationship between the specific intensity of radiation and second-order coherence function of the wavefield. It is shown in the present paper that for propagation in free space, Tatarskii's assumption restricts the validity of his theory to fields that are statistically homogenous.

2. M. S. ZUBAIRY and E. WOLF

EXACT EQUATIONS FOR RADIATIVE TRANSFER OF ENERGY AND MOMENTUM IN FREE ELECTROMAGNETIC FIELDS

OPT. COMMUN. 20, 321 (1977)

In a recent paper a new theory of radiative energy transfer in free electromagnetic fields was formulated. The basic quantities in this theory are the so-called angular components of the average electromagnetic energy density and of the average Poynting vector. In the present paper it is shown that these angular components obey differential equations that may be considered to be rigorous equations for the radiative transfer of energy and of momentum in free electromagnetic fields.

3. M. D. SRINIVAS and E. WOLF

STOCHASTIC EQUATIONS FOR CLASSICAL AND QUANTUM DISTRIBUTION FUNCTIONS

STATISTICAL MECHANICS AND STATISTICAL
METHODS IN THEORY AND APPLICATION
Edited by Uzi Landman
(Plenum Publishing Corporation, 1977)

A stochastic process may be characterized by multi-time distribution functions of all orders, whose time-evolution has up to now been studied mainly in the context of the Markov process; in such a case it is sufficient to determine the time-evolution of the distribution function of the lowest order only. In the present article stochastic differential equations for the distribution functions of all orders are derived, with no restriction on the nature of the random process. These equations are natural generalizations of the Kramer-Moyal differential equation for the first-order distribution either of infinite order, or at most of the second order.

III. SUMMARIES (cont'd)

4. E. COLLETT and E. WOLF

IS COMPLETE SPATIAL COHERENCE NECESSARY FOR THE GENERATION OF HIGHLY DIRECTIONAL LIGHT BEAMS?

OPT. LETTERS 2, 27 (1978)

An equivalence theorem is formulated that provides conditions under which planar sources of different states of spatial coherence will generate optical fields that have identical far-zone intensity distributions. As an example, a partially coherent source whose linear dimensions are large compared with the correlation length of the light across the source is described that will generate a field whose far-zone intensity distribution is identical with that of a Gaussian laser beam.

5. A. T. FRIBERG

ON THE QUESTION OF THE EXISTENCE OF NONRADIATING PRIMARY PLANAR SOURCES OF FINITE EXTENT

J. OPT. SOC. AMER. 68, 1281 (1978)

It is known that certain oscillating three-dimensional charge-current distributions do not radiate. In this paper we show that no monochromatic, well-behaved, two-dimensional scalar source distribution that is localized within a finite area may be nonradiating. We also generalize this result to fluctuating, stationary planar source distributions of any arbitrary state of coherence.

6. A. T. FRIBERG

ON THE EXISTENCE OF A RADIANCE FUNCTION FOR A PARTIALLY COHERENT PLANAR SOURCE

COHERENCE AND QUANTUM OPTICS IV
Edited by L. Mandel and E. Wolf
(Plenum Publishing Corporation, 1978, Paper TF-4)

In recent years a considerable amount of effort has been devoted to the study of radiometry with partially coherent, statistically stationary planar sources. The traditional radiometric quantities, generally believed to apply to incoherent sources, have been generalized to pertain to sources of any state of coherence. The generalized formalism is in the framework of second-order coherence theory and the generalized radiometric quantities are linear in the cross-correlation function of the field at two points in the source plane.

III. SUMMARIES (cont'd)

6. (cont'd)

Of basic importance in the representation of the radiometric properties of a source is the radiance function, which is a function of position $\underline{r}$ in the source plane and of direction $\underline{s}$, into which the source radiates. Traditionally the radiance has been defined via geometrical arguments as the rate at which energy is emitted by the source per unit projected source area around the point $\underline{r}$ and per unit solid angle around the direction $\underline{s}$, the projection of the source area being onto the plane perpendicular to the direction $\underline{s}$. Recently several different definitions have been given for the radiance function in terms of the cross-correlation function of the field at the source plane. It was pointed out by Marchand and Wolf, however, that at least the commonly used radiance function originally proposed by A. Walther cannot be considered as true measure of energy distribution. In particular, they showed that these generalized radiance functions may occasionally take on negative values. It has also been shown in earlier investigations by Marchand and Wolf that irrespective of the particular form chosen for the radiance function the radiant intensity in the direction $\underline{s}$, which is defined as the rate at which energy is emitted by the source per unit solid angle around the direction $\underline{s}$, is always related in a definite way to the four-folded Fourier transform of the cross-correlation function of the field at the source plane with the transform parameters proportional to the components of the projection of $\underline{s}$ onto the source plane.

It is shown in the present paper that no radiance function, which is linear in the cross-correlation function of the field at the source plane and which results in the correct radiant intensity, can be given the traditional geometrical interpretation as described above for all states of coherence of the source. More specifically, it is shown that there is no radiance function which simultaneously satisfies the requirements that it (a) is linear in the cross-correlation function at the source plane, (b) is non-negative for all possible values of its arguments, (c) yields the correct radiant intensity, and (d) vanishes in the source plane outside the source area.

It seems worthwhile mentioning that the present situation in radiometry is somewhat analogous to that encountered a long time ago in the so-called phase-space formulation of quantum mechanics. In that representation the expectation values of quantum mechanical operators are calculated in phase-space using the methods of classical statistical mechanics. It has been shown that there is no non-negative distribution function in phase-space that would give the correct marginal distributions for position and momentum (Wigner's theorem). The two radiance functions introduced by A. Walters for radiometry with partially coherent fields are in many respects analogous to two commonly used quantum mechanical phase-space distribution functions: his original definition of radiance is analogous to the well-known Wigner distribution function, and his later definition of radiance is analogous to another widely used quantum distribution function, originally due to Margenau and Hill. These phase-space distribution functions, like the corresponding radiance functions, may in general become negative and are sometimes referred to as quasi-probabilities.

III. SUMMARIES (cont'd)

7. E. WOLF and M. S. ZUBAIRY

RADIATIVE ENERGY TRANSFER IN SCALAR WAVE FIELDS

COHERENCE AND QUANTUM OPTICS IV
Edited by L. Mandel and E. Wolf
(Plenum Publishing Corporation, 1978)

In recent years several attempts have been made to provide a satisfactory basis for the theory of radiative energy transfer in optical fields. The conventional theory, on which many investigations in astrophysics and in the field of atmospheric propagation are based, was developed quite independently of modern theories of radiation; consequently its range of validity is not understood at the present time.

We recently put forward a new theory of radiative energy transfer in free elctromagnetic fields, based on second-order coherence theory. This theory, which takes into account both correlation and polarization properties of the field differs in some respect from the conventional theory, but it reduces to it in certain limiting cases. Moreover, it provides a precise interpretation of some of the basic concepts, (such as the specific intensity of radiation), employed in the traditional heuristic model for energy transport. In attempting to extend this theory to fields that interact with matter, it seems advisable to consider first a scalar model, i.e. to ignore specific effects arising from the state of polarization of the field.

In the first part of this paper we outline a simplified scalar analogue of the theory that we developed. We then show how the concepts of angular components of the average energy density and of the average flux vector, that are basic in our earlier work, may be introduced for any stationary ensemble of scalar wavefields. These quantities will be shown to be expressible in terms of certain second order correlation functions of the field. Some preliminary work relating to the derivation of the appropriate transport equations for these quantities will also be discussed.

8. M. S. ZUBAIRY

RADIATIVE ENERGY TRANSFER IN THE PRESENCE OF
RANDOM SOURCE DISTRIBUTIONS

COHERENCE AND QUANTUM OPTICS IV
Edited by L. Mandel and E. Wolf
(Plemun Publishing Corporation, 1978)

Radiative energy transfer is generally treated on the basis of a phenomenological theory that bears no apparent relationship to the theory of the electromagnetic field. In recent years, progress has been made to elucidate the foundations of the theory of radiative transfer. A new theory of radiative transfer in free fields has been developed recently, which clarifies the relationship between the stochastic theory of the

III. SUMMARIES (cont'd)

8. (cont'd)

electromagnetic field and the phenomenological theory. The status of the theory of radiative transfer in the presence of the random source distribution and the random inhomogeneity of the medium is, however, still far from satisfactory.

In this paper, we investigate the problem of wave propagation in a medium with random source distribution on the basis of the stochastic scalar wave equation. The investigation is related to some extent to that of Keller.

We employ the definition of specific intensity of radiation in terms of the second order correlation function of the field as first proposed by Ovchinnikov and Tatarskii. On the basis of this definition we derive exact equations of radiative transfer relating to the wave propagation in the presence of random sources. Our results reveal the significance of the source function that is usually introduced formally in the phenomenological theory.

9. E. WOLF

THE RADIANT INTENSITY FROM PLANAR SOURCES OF ANY STATE OF COHERENCE

J. OPT. SOC. AMER. 68, 1597 (1978)

A new formula is derived for the radiant intensity from any steady, finite, primary or secondary planar source of any state of coherence. It expresses the radiant intensity as a two-dimensional spatial Fourier transform of a quantity that represents a correlation function of the field in the source plane, averaged over the area of the source. The formula may be regarded as a natural counterpart for fields generated by partially coherent sources to the well-known two-dimensional Fourier transform relation between the field distributions in the plane of a finite coherent source and in the far zone. Some implications of the new formula are discussed. An alternative expression is also obtained that is applicable when the source is a primary one and it is shown to imply that the radiant intensity is then a boundary value on two real axes of an entire analytic function of two complex variables.

III. SUMMARIES (cont'd)

10. A. T. FRIBERG

ON THE EXISTENCE OF A RADIANCE FUNCTION FOR FINITE PLANAR SOURCES OF ARBITRARY STATES OF COHERENCE

J. OPT. SOC. AMER. 69, 192 (1979)

In this paper we show that one cannot associate a radiance function with a finite partially coherent planar source of arbitrary state of coherence that would have all the usual properties attributed to it in elementary radiometry. More specifically, we show that in general there is no radiance function which depends linearly on the correlations existing between any pair of points in the source plane, gives the correct angular distribution of radiant intensity and which, moreover, is nonnegative and vanishes outside the source area. However, regardless of this result, the concept of generalized radiance appears to be a useful mathematical tool in radiometry with partially coherent sources.

11. J. T. FOLEY and E. WOLF

NOTE ON THE FAR FIELD OF A GAUSSIAN BEAM

J. OPT. SOC. AMER. 69, 761 (1979)

It is shown that contrary to some recent claims the far field of a Gaussian beam does not contain contributions from high spatial frequency components of the source. Consequently, no evanescent waves take part in the formation of the far field. Corresponding results for other types of wave fields are also briefly discussed.

12. E. WOLF and E. COLLETT

PARTIALLY COHERENT SOURCES WHICH PRODUCE THE SAME FAR-FIELD INTENSITY DISTRIBUTION AS A LASER

OPT. COMMUN. 25, 293 (1978)

It is shown that certain partially coherent model sources whose intensity distribution and degree of coherence are both gaussian will generate the same far-field intensity distribution as a completely coherent laser source.

III. SUMMARIES (cont'd)

13. R. ROY and M. S. ZUBAIRY

ANALYTIC SOLUTIONS OF THE OPTICAL BISTABILITY EQUATIONS FOR A STANDING WAVE CAVITY

SUBMITTED TO OPT. COMMUN.

The problem of optical bistability in a standing wave cavity in the steady state leads to a pair of coupled, nonlinear, ordinary differential equations for the forward and backward waves. Only numerical solutions have so far been presented for these equations. We give their exact analytic solutions and find good agreement with the numerical results. The exact solutions are shown to reduce to the mean field equation for the input and output fields in the double limits $T \to 0$ and $\alpha L \to 0$ for the mirror transmission and the linear absorption coefficient, respectively.

14. M. S. ZUBAIRY

RADIATIVE ENERGY TRANSFER IN A RANDOMLY FLUCTUATING MEDIUM

SUBMITTED TO J. OPT. SOC. AMER.

The basic laws of the phenomenological theory of radiative energy transfer are derived, under certain conditions, within the framework of the stochastic scalar wave theory. Generalized expressions are introduced for the "angular components" of the energy density and of the energy flux vector. An equation is derived for the coherence function of the wave-field in a randomly fluctuating medium using perturbation theory. This approach is compared with the quantum field theoretic method based on the Dyson equation and the Bethe-Salpeter equation. Finally, an equation of radiative energy transfer of the form employed in the phenomenological theory is derived for wave propagation in a statistically quasihomogeneous medium. Our results relate the extinction and the scattering coefficients (which are introduced heuristically in the conventional theory of radiative energy transfer) to the stochastic characteristics of the medium.

III. SUMMARIES (cont'd)

15. R. ROY and M. S. ZUBAIRY

BEYOND THE MEAN FIELD THEORY OF DISPERSIVE OPTICAL BISTABILITY

SUBMITTED TO PHYS. REV. A

The problem of dispersive optical bistability has so far been treated only in the mean-field approximation. A rigorous justification of the mean-field theory can only be obtained from exact solutions of the steady state Maxwell-Bloch equations which retain the spatial dependence of the field. In this paper, we present exact analytic solutions to these equations. We demonstrate that the mean field equation connecting the input and the output fields follows naturally from these solutions in the limits $T \to 0$, $\delta_F \to 0$ and $\alpha L \to 0$ for the mirror transmission coefficient, the detuning of the field from the cavity resonance and the linear absorption respectively, with $\frac{\alpha L}{2T}$ and $\delta_F L/2cT$ remaining finite. No constraint is placed on the detuning of the laser field from the atomic resonance frequency. We illustrate our results with the help of graphs showing the output intensity vs. the input intensity for different values of the relevant parameters. The effect of these parameters on the phase shift of the output field is also displayed.

16. S. SINGH and M. S. ZUBAIRY

QUANTUM THEORY OF A TWO-MODE LASER WITH COUPLED TRANSITIONS

SUBMITTED TO PHYS. REV. A

The quantum statistical properties of the optical field of a two-mode laser with two coupled transitions have been studied using a generalization of the Scully and Lamb (1967) theory. The photon number distribution and the mode intensity distribution are obtained in the steady state for a system of homogeneously broadened atoms in resonance with the laser field. It is shown that the mode coupling constant ξ is unity and that near threshold the results of earlier treatments are recovered. Furthermore, it is shown that certain limit measures for the relative intensity fluctuations predicted by the semiclassical Fokker-Planck treatments based on the third order theory are valid even in the limit of arbitrarily high gain levels.

III. SUMMARIES (cont'd)

17. M. S. ZUBAIRY

EFFECT OF COOPERATIVE ATOMIC INTERATIONS ON PHOTON STATISTICS IN A SINGLE-MODE LASER

TO BE PUBLISHED IN PHYS. REV. A

The effect of cooperative atomic interactions on the photon statistics in a single-mode laser is studied on the basis of an equation of motion for the reduced density operator of the field that was recently derived by Huang and Mandel. The corresponding anti-normal ordering distribution function is shown to satisfy a Fokker-Planck equation. The steady state solution of this equation is used to determine the photon number distribution, the average intensity and the intensity fluctuation.

18. E. COLLETT and E. WOLF

BEAMS GENERATED BY GAUSSIAN QUASI-HOMOGENEOUS SOURCES

SUBMITTED TO OPT. COMMUN.

An explicit expression is presented for the cross-spectral density function of the light in any cross-section perpendicular to the axis of a beam generated by a planar, steady-state, quasi-homogeneous source, whose intensity distribution and degree of spatial coherence are both Gaussian. The result is used to discuss some properties of such a beam. It is found, in particular, that the ratio of the transverse (spatial) coherence length of the light to the beam width is the same for every cross-section perpendicular to the beam axis.

19. A. T. FRIBERG

EFFECTS OF COHERENCE IN RADIOMETRY

APPLICATIONS OF OPTICAL COHERENCE
PROC. SOC. PHOTO. OPT. INSTR. ENGS., 194, (1979) (In Press)

Radiometry evolved over a long period of time around rather incoherent sources of thermal nature. Only during the last few years the effects of coherence have been begun to be taken into account in radiometric considerations of light sources. In this review article the fundamental concepts of conventional radiometry and of the theory of partial coherence will be first briefly recalled. The basic radiometric quantities, namely the radiance, the radiant emittance and the radiant intensity, associated with a planar source of any state of coherence will then be introduced. It will be pointed out that the radiant intensity, representing the primary measurable quantity, obeys in all circumstances the usual postulates of conventional radiometry, whereas the radiance and the radiant emittance turn out to be much more elusive concepts. The radiometric characteristics of light from incoherent and coherent sources as well as from a certain type of a partially coherent source, viz., the so-called quasihomogeneous source, will be analyzed. Quasihomogeneous sources are useful models for radiation sources that are usually found in nature. Lambertian sources will be discussed as examples.

IV. ADVANCED DEGREE EARNED BY A GRADUATE RESEARCH ASSISTANT WHILE EMPLOYED ON THIS PROJECT

M. S. ZUBAIRY, PH.D. degree, University of Rochester (1978)

Title of Thesis: "A Study in the Foundation of the Theory of Radiative Energy Transfer."

IV. LIST OF SCIENTIFIC PERSONNEL

The following persons assisted in the research under this grant:

E. WOLF, Professor of Physics, Principal Investigator

J. T. FOLEY, Research Assistant (9/71-7/77); Research Associate (7/77-7/79)

M. S. ZUBAIRY, Research Assistant (9/74-10/78); Research Associate (10/78-8/79)

A. WAJID, Research Assistant, Part-Time

J. YEH, Research Assistant

A. FRIBERG, Research Assistant, Part-Time